Oscilloscope I: Using the Oscilloscope

(K. M. Westerberg, 8/2004)

Introduction

In this lab, you will be introduced to two new pieces of equipment, the oscilloscope and the function generator. The main purpose of this lab is to learn how to operate these two devices. You will be using both the oscilloscope and the function generator in many of the remaining 4BL labs, as well as in a number of 4CL and 4DL labs, so it is important that you become familiar with them.

The function generator is an AC power source. It is designed to produce a voltage signal which varies with time. Various controls allow the user to adjust the frequency, amplitude, DC offset, and waveform of the voltage signal. There really isn't much to learning how to use this device, but it is very important that you understand the nature of the voltage signal it produces, and in particular, what the terms "frequency", "amplitude", and "DC offset" mean.

The main purpose of the oscilloscope is to plot a voltage signal as a function of time (it is also possible to plot one voltage signal versus another — you will learn about that in the Oscilloscope II Lab). An oscilloscope is basically a Cathode Ray Tube with a number of sophisticated controls to help control how the voltage signal is displayed. The voltage signal to be plotted is connected to the vertical deflection plates. The horizontal deflection plates are connected to a voltage source which varies at a constant rate in time. As time passes, the electron beam deflects vertically in proportion to the input voltage signal and horizontally in proportion to the time elapsed. The result is a plot of V vs. t on the screen (the plot as it appears on the oscilloscope screen is often called a "trace"). Various parameters, such as the vertical and horizontal deflection factors, can be adjusted by the user.

You will quickly discover that the oscilloscope you are using offers an enormous amount of functionality — the oscilloscope is a very complicated instrument. Indeed, there are features on the oscilloscope that you are unlikely to encounter, either as a student or as a professional. In this lab, you will be concentrating on the most basic (and most important) features of the oscilloscope. A more comprehensive (although by no means complete) list of oscilloscope features can be found in the "Oscilloscope Instructions" (separate handout).

One oscilloscope control which somehow got left off of the instruction pages is the oscilloscope reset function. To reset the oscilloscope to a "standard state", press the TEXT OFF and STATUS buttons at the same time (these two buttons surround the menu buttons just to the right side of the oscilloscope screen). You should always reset the oscilloscope when you first start using it, in order to undo any changes made by the previous user, and to provide yourself with a predictable starting configuration. You can also reset the oscilloscope if you get messed up and somehow put the oscilloscope into a state you do not understand. It is very difficult to permanently damage the oscilloscope simply by pushing buttons and

turning knobs (exceptions listed below).

The oscilloscope, like any other piece of equipment, can be damaged if mistreated. The following rules should be adhered to (many of these rules apply to electronic devices in general):

- Before plugging or unplugging the oscilloscope, make sure it is turned off (make sure the power button is pushed out).
- Don't force anything. If one of the connectors seems stiff, use patience rather than brute force.
- No food or drink in the lab (this is a general rule in the lab, but it is especially important to adhere to this rule when working with the oscilloscopes).
- Do not turn the trace intensity or text intensity too high, as this can damage the screen in the long run. The oscilloscope trace really shouldn't be brighter than is necessary to see the trace easily. You may find it necessary to adjust the trace intensity when making certain adjustments to the oscilloscope.

Following below are the exercises for this lab. It is a long lab, so your instructor may elect to omit (or postpone) individual sections.

A Periodic signals

In principle, an oscilloscope can display any voltage signal, no matter how it depends on time. In practice, the oscilloscope is most useful when the voltage signal is *periodic* (i.e., the voltage signal repeats itself exactly after a certain period of time) because then the oscilloscope will display the same signal over and over again — the result is a stable image on the oscilloscope screen. Fortunately, most voltage signals of practical interest are periodic.

One of the simplest examples of a periodic voltage signal is the "sine wave", depicted in Fig. 1. The *period* of such a signal is defined to be the amount of time elapsed before the signal repeats itself. The *frequency* is the reciprocal of the period. The SI unit of frequency is cycles per second, or Hertz (Hz). The *peak-to-peak amplitude* is the difference between the highest and lowest voltage during one cycle. The *amplitude* is half of the peak-to-peak amplitude, and represents the difference between the highest and the middle (average) value of the voltage during the cycle. Normally one thinks of a sine wave as oscillating around an average voltage value of zero, although in general the average voltage level can take any value. The *DC offset* is another name for this average voltage. These definitions are illustrated in Fig. 1 for the sine wave, although most of these definitions work equally well with *any* periodic voltage signal.

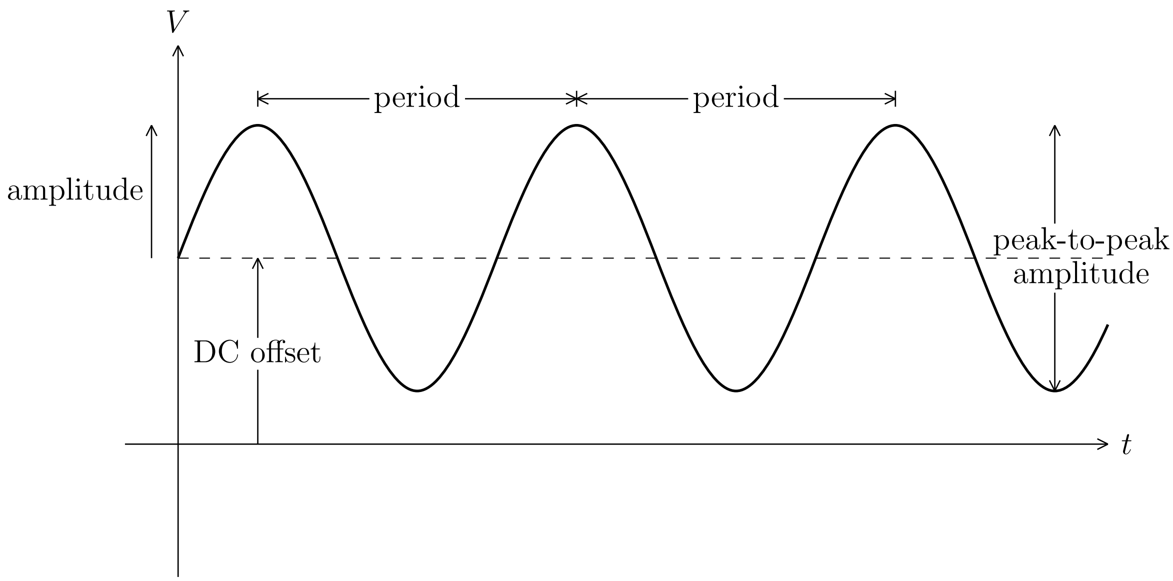

Figure 1: A generic sine-wave voltage signal, with period, peak-to-peak amplitude, amplitude, and DC offset indicated.

A sine-wave voltage signal is uniquely determined by its frequency, amplitude, and DC offset.[1] A function generator can be used to generate any sine-wave voltage within a wide range of frequency, amplitude, and DC offset values. The function generator can also be used to generate a square-wave and a triangle-wave voltage signal.

The exercises in this section are designed to familiarize students with the concepts introduced above, and to get used to using the function generator and the oscilloscope. To get started, connect the function generator to channel 1 of the oscilloscope. Turn on the oscilloscope and reset it. Turn on the function generator and set it to sine-wave. Set the frequency to a value somewhere in the 200–400 Hz range, and set the amplitude and DC offset to reasonable values. Adjust channel 1's VDF (Vertical Deflection Factor) so that the oscilloscope trace fits on the screen.

(Q-1) Adjust the frequency dial on the function generator back and forth, and explain what happens to the oscilloscope trace as you do this. Sketch the oscilloscope trace for two different frequencies, and use these sketches in your explanation.

Note: It shouldn't take more than a minute to draw each of these sketches. The sketches should be accurate enough so that it is clear from examining them what happens to the signal when the frequency (and nothing else) is changed, but the graphs do not have to be exactly right.

(Q-2) Now increase the frequency by a factor of 10. What button (on the function generator) did you press to accomplish this? What happened to the oscilloscope trace?

[1] Actually, that's not quite true — in addition to these three quantities, one also needs to know a *phase angle* (or equivalently, a *time shift*). However, the oscilloscope (under normal operation) will display the same trace regardless of the phase angle.

(Q-3) Now adjust the MTB (Main Time Base) of the oscilloscope. What happens to the trace when you do this? Is it possible to adjust the MTB to restore the oscilloscope trace to what it looked like before you increased the frequency by a factor of 10?

(Q-4) Adjust the amplitude dial on the function generator back and forth, and explain what happens to the oscilloscope trace as you do this. Sketch the oscilloscope trace for two different amplitudes, and use these sketches in your explanation (again, these sketches only need to be accurate enough to make your point — they do not have to be exactly right).

(Q-5) Adjust the DC offset dial on the function generator back and forth, and explain what happens. Sketch the oscilloscope trace for two different DC offsets, and use these sketches in your explanation.

(Q-6) Now switch the function generator from sine-wave to square-wave, and then to triangle-wave. Do not adjust the frequency, amplitude, or DC offset while you do this. Sketch each waveform.

(Q-7) You should have noticed that adjusting the MTB on the oscilloscope changed the oscilloscope trace in much the same way as adjusting the frequency on the function generator. Likewise, adjusting the VDF on the oscilloscope produces the same changes in the trace as adjusting the amplitude on the function generator, and adjusting the vertical position on the oscilloscope and the DC offset on the function generator will also produce the same changes in the trace (try it). There is, however, a very important difference between adjusting the function generator and adjusting the oscilloscope. What is it?

B Determining period, frequency, and amplitude

The oscilloscope can be used to measure the frequency and amplitude of a voltage signal. You don't have to rely on reading the frequency dial on the function generator.

To get started, switch the function generator back to sine-wave and adjust the function generator and/or the oscilloscope to produce a suitable oscilloscope trace. The oscilloscope trace should be centered vertically, large enough to just about fill the screen, and should contain at least two full periods. Once you have completed these adjustments, do not adjust the function generator for the rest of this section.

(Q-8) Plot the oscilloscope trace as a voltage vs. time graph in your lab notebook. *This graph must be drawn accurately, as you will be using this graph for calculations.* The vertical and horizontal axes must be labeled with appropriate voltage/time units, as if you were plotting a real graph (in fact, you *are* plotting a real graph). The graph should occupy one full page.

(Q-9) From your graph, determine the period and the peak-to-peak amplitude of the signal (show on your graph how you do this). Use these two values to calculate the frequency and the amplitude of the signal. Compare the frequency you calculated with the frequency obtained from the function generator. Is the frequency dial on the function generator accurate?

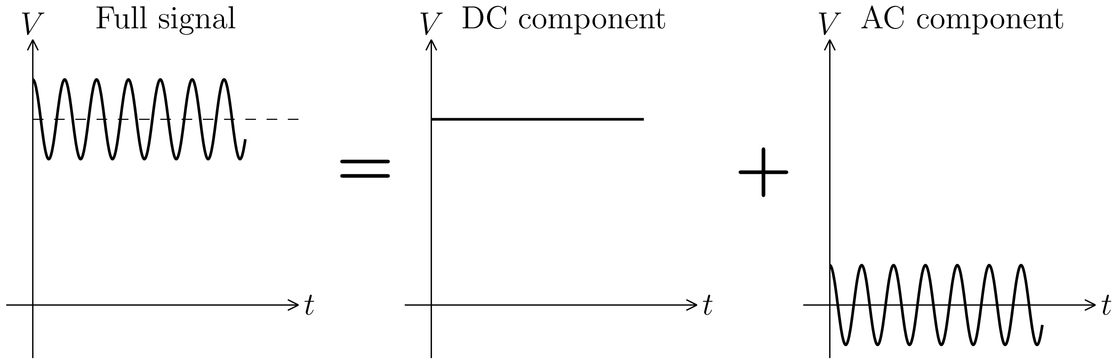

Figure 2: Illustrates the decomposition of a voltage signal into its DC and AC components. Although a sine wave is depicted above, any voltage signal can be decomposed into AC and DC components.

The oscilloscope provides "cursors", which can be used to determine the period, frequency, and amplitude directly from the oscilloscope trace. Pressing the CURSORS button on the oscilloscope calls up the cursors menu. Menu items can be selected by pushing the corresponding menu button just to the right of the oscilloscope screen.

(Q-10) Using the vertical cursors, determine the period and frequency of the signal directly from the trace. The vertical cursors (i.e., the two vertical lines) can be adjusted using the TRACK and DELTA knobs. The time difference between the cursors appears on the oscilloscope screen (already taking the MTB into account). By appropriately adjusting the cursors, the period of the signal can be determined. The oscilloscope can also be made to display the frequency by selecting $1/\Delta T$ from the READOUT submenu.

(Q-11) Using the horizontal cursors, determine the peak-to-peak amplitude of the signal directly from the trace. You can switch between vertical and horizontal cursors using the menu. The TRACK and DELTA knobs then control the horizontal cursors in much the same way that they controlled the vertical cursors before.

(Q-12) Compare the frequency, period, and peak-to-peak amplitude values obtained using cursors with the values obtained from your own graph. Which set of values do you think are more accurate?

(Q-13) The peak-to-peak amplitude can be determined by the oscilloscope automatically. Adjust the horizontal cursors so that they are no longer lined up with the trace, and then select "Vpp" from the cursors menu. The oscilloscope will automatically line up the horizontal cursors with the trace. Compare this peak-to-peak amplitude with your previous values.

C AC and DC mode

Any time-varying voltage can be expressed as a sum of its DC and AC components, as illustrated in Fig. 2. As can be seen from that figure, time-varying voltage signals tend to vary around some average voltage level. That average voltage level is the DC component of the original voltage signal. The AC component has the same overall shape as the original voltage signal, but varies around zero voltage. The sum of these two components will yield the original voltage signal.

Often it is the case that the most interesting feature of a voltage signal is its shape (i.e., how it varies with time) — the DC component is not so important. In such cases, it may be difficult to observe the time-variation of the voltage signal if the DC component is relatively large compared to the AC component. It would be nice in such cases if we could subtract out the DC component and only display the AC component. With the relatively large DC component gone, we would be able to amplify the remaining AC voltage signal (by decreasing the VDF) to make it more visible on the oscilloscope screen.

It turns out that the oscilloscope will allow us to do this. Each channel can be displayed in either "DC mode" or "AC mode". A voltage signal displayed in DC mode is displayed normally — the entire voltage signal (the sum of its DC and AC components) is displayed on the oscilloscope screen. However, if a voltage signal is displayed using AC mode, only its AC component is displayed — the DC component is effectively subtracted out. The oscilloscope is normally set to use DC mode, but you can switch between AC and DC mode for a given channel by pressing the AC/DC button corresponding to that channel. The current selection is indicated by the symbol following the VDF for a displayed channel: an equal sign (=) for DC mode or a tilde (∼) for AC mode.

(Q-14) Make sure that the oscilloscope is set to DC mode for channel 1, and that the function generator frequency is at least 1000 Hz. Adjust the DC offset dial on the function generator back and forth and describe what happens to the oscilloscope trace. Now switch the oscilloscope to AC mode and continue to adjust the DC offset dial on the function generator. What happens to the oscilloscope trace in this case? Why?

AC mode is implemented inside the oscilloscope by inserting a capacitor into the oscilloscope's internal circuit, as shown in Fig. 3. If a DC voltage is applied to the oscilloscope, the capacitor fully charges in a relatively short time, and no voltage remains over the deflector plates — the oscilloscope will record zero voltage. If the input voltage changes over time, the capacitor attempts to follow the input voltage, but charging/discharging the capacitor requires *time* (current has to pass through the big resistor). If the input voltage changes too quickly, the capacitor is not able to follow those changes, and the input voltage signal ends up passing through to the deflector plates (the deflector plates themselves require *much* less time to charge/discharge because their capacitance is so small) — the oscilloscope will record the AC voltage signal.

In the more general case where the input voltage has both an AC and a DC component,

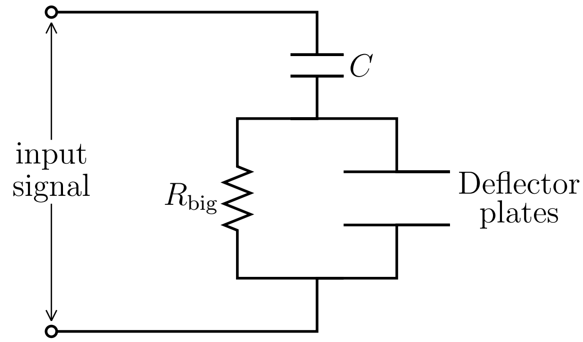

Figure 3: Circuit (simplified) inside the oscilloscope when the displayed channel is set to AC mode. The input signal is connected to the oscilloscope as indicated above. Over a reasonable time, the capacitor C will charge up to a voltage equal to the DC component of the input signal, leaving just the AC component over the deflector plates. The oscilloscope will display the AC component. When the oscilloscope is set to DC mode, the capacitor C is removed from the circuit — the voltage over the deflector plates will equal the complete input signal.

the capacitor will (over a short time) charge up to a voltage equal to input signal's DC component. This effectively subtracts out the DC component, leaving only the AC component for the deflector plates. The oscilloscope will display the AC component on the screen.

This is quite an elegant design, but there is a problem with it. Suppose that the input voltage changes over time, but rather slowly. In this case, the capacitor may be partially successful in following the input voltage, and part of the AC voltage signal may get subtracted out. If the frequency of the AC signal is low enough, this can lead to a reduction in the amplitude, and can even lead to distortions if the input signal is not a sine wave.

(Q-15) Make sure that the oscilloscope is set to DC mode and the function generator is set to sine-wave, and reduce the generator frequency to 20 Hz. Slowly turn down the frequency. Does the amplitude change as you do this? Would you have expected it to? Now set the oscilloscope to AC mode and repeat the experiment. What happens in this case as you turn down the frequency? Can you explain why?

(Q-16) Now reset the generator frequency to 20 Hz and the oscilloscope to DC mode. Switch the function generator to square-wave. The oscilloscope trace should not surprise you. Now switch the oscilloscope to AC mode and sketch the oscilloscope trace. Why do you suppose the trace looks this way?

D The AUTOSET button

A number of future labs will recommend that you press the AUTOSET button on the oscilloscope after setting up the circuit and connecting it to the oscilloscope. The AUTOSET button can be a very convenient tool, but it can also mess up your results if you don't know

what you are doing. What this button basically does is reconfigure the oscilloscope so as to display the voltage signal in the most appropriate manner, resetting the VDF and MTB, among other things.

So, who decides how the oscilloscope should be reconfigured to display the voltage signal? The *oscilloscope* decides, and that is what makes the button dangerous. Pressing the AUTOSET button could easily configure the oscilloscope in ways you do not understand or want. It is always dangerous to let a machine do your thinking for you.

(Q-17) Reset the oscilloscope. Set the function generator to a 20000 Hz sine wave (choose some reasonable amplitude and DC offset), and then press the AUTOSET button. What happens? Can you see the usefulness of this button?

(Q-18) Now set the function generator to a 20 Hz square wave, and again press the AUTOSET button. What happens in this case? Is the oscilloscope trace what you expected? Can you explain what happened? Do you think you would have been able to explain it if you hadn't performed the exercises in Section C?

E Triggering

Consider the periodic voltage signal given in Fig. 4(a). In principle, this V vs. t graph will continue out to $t \to \infty$ as the voltage signal connected to the oscilloscope continues to vary sinusoidally indefinitely. However, the oscilloscope cannot display the entire graph because the screen is only 10 divisions wide. What the oscilloscope does, in fact, is it starts the electron beam on the left side of the screen at some initial time and then allows the beam to "sweep" across the screen, plotting V vs. t during this time. Once the beam disappears off the right side of the screen, the oscilloscope causes the beam to jump back to the left side of the screen where it begins a new sweep, possibly after a short time delay. The stable image you see on the oscilloscope screen is actually a result of repeated sweeps executed at different times. The image is stable because the voltage signal is periodic — the voltage signal repeats itself after a certain period of time, and so the same graph gets plotted every time.

Does a periodic voltage signal always result in a stable image on the oscilloscope screen? You may guess that the answer is yes, because that is what the oscilloscope has been displaying during the lab exercises. However, to get the stable image requires good timing on the part of the oscilloscope — it is necessary that the oscilloscope begins each sweep at the exact same point in the cycle. To see why this is necessary, examine Fig. 4(b). The start times for each sweep are indicated with arrows. In this case, the sweeps do *not* begin at consistent points in the cycle. Fig. 4(d) shows the corresponding oscilloscope display. Because of the inconsistent sweeps, the image jumps around a lot — each successive trace is different, and so the image appears unstable. Now examine Fig. 4(c) for contrast. In this case, the sweeps do begin at consistent points in the cycle, and the result is the stable oscilloscope image depicted in Fig. 4(e).

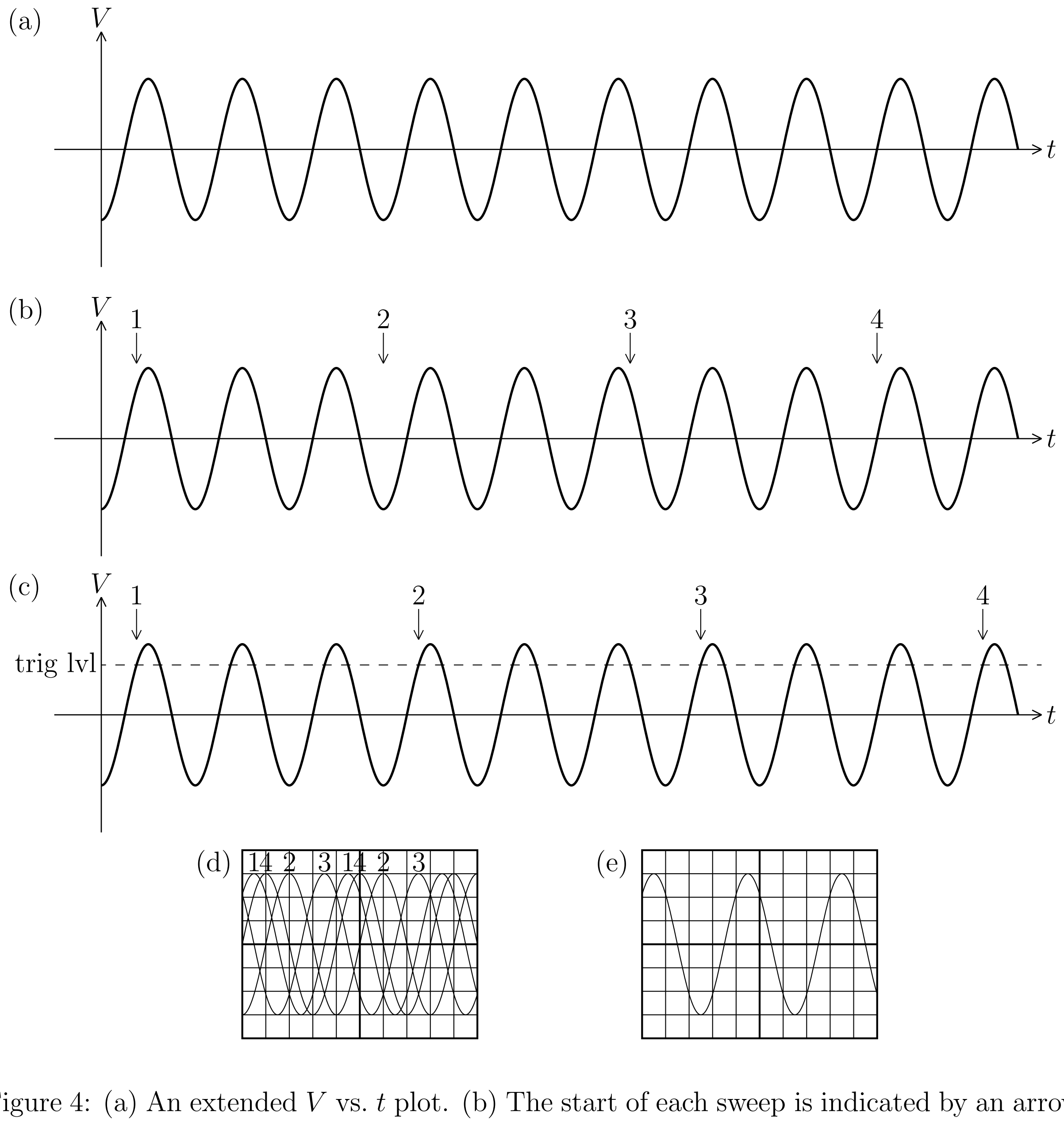

Figure 4: (a) An extended V vs. t plot. (b) The start of each sweep is indicated by an arrow. The sweeps in this case do not begin at a consistent part of the cycle. (c) The sweeps in this case all begin when the signal crosses the indicated trigger level, and therefore begin at a consistent part of the cycle. (d) The jumbled oscilloscope image resulting from the sweeps indicated in (b). (e) The stable oscilloscope image resulting from the sweeps indicated in (c).

So how does the oscilloscope manage to produce a stable image every time? The answer has to do with "triggering", which has to do with how the oscilloscope decides, once one sweep is finished, when to begin the next sweep. The most reliable way of ensuring that each sweep begins at the same part of the cycle is to base the start of each sweep on the voltage level of the input signal.

Triggering is completely specified by the following, all of which can be adjusted by the user:

1. Which input voltage (i.e., which channel) is used for triggering? By default, triggering is based on channel 1, although the user can select any of the four channels for this purpose, and can alternatively specify that triggering be based on the "line voltage" (which comes from the outlet).

2. What is the "trigger level", that is, the voltage level at which sweeping is to begin (see Fig. 4(c))? The user can adjust the trigger level using the LEVEL MTB knob.

3. Should the new sweep begin when the trigger voltage reaches the trigger level "on the way up" (from low voltage to high voltage), or "on the way down"? By default, sweeping begins when the trigger voltage is crossed on the way up.

The reason for this last specification is the fact that for any periodic signal, any voltage level crossed by that signal must be crossed at least twice — once on the way up, and again on the way down. If sweeping were allowed to begin at either crossing, two images may appear on the oscilloscope screen instead of one.

All three triggering specifications can be adjusted by the user. The trigger level (item 2 above) can be adjusted by turning the LEVEL MTB knob. The trigger channel and direction (items 1 and 3 above) can be adjusted from the TRIGGER MTB menu. Alternatively, these two selections can be adjusted using the "⨍ ⨏" buttons for each channel. For example, pushing the "⨍ ⨏" button for channel 2 selects channel 2 as the trigger voltage, and switches between "on the way up" (⨍) and "on the way down" (⨏).

By default, triggering is based on channel 1's voltage and sweeping begins when the trigger level is crossed on the way up. The current selection of channel and direction appears in the lower right corner of the display (e.g., "ch1 ⨍"). The trigger level is normally not visible on the oscilloscope, but you can make it visible by following the instructions on the last page of the oscilloscope instructions (under the heading "To view trigger level ("T"-symbol)").

To perform the exercises in this section, first set up the function generator and the oscilloscope to display a reasonable sine wave. Shift the trace horizontally to the right (using the X POS knob) in order to make the start of the trace obviously visible on the screen. Then make the trigger level visible by following the steps outlined in the oscilloscope instructions (see above). The trigger level should now be indicated on the oscilloscope with a "T–" symbol on the far left of the screen.

(Q-19) Adjust the trigger level up and down, always remaining within the peak-to-peak voltage range of the signal, and explain what you see. Does it make sense? Sketch the trigger-level indicator and the resulting trace.

(Q-20) Now increase the trigger level until it rises above the highest voltage reached by the trace. What happens and why? Return the trigger level to the middle of the trace.

(Q-21) Switch the function generator to square-wave, and then adjust the trigger level up and down (always remaining within the peak-to-peak voltage range). What happens to the trace in this case? How is this different from (Q-19)?

(Q-22) Switch the function generator back to sine-wave, and press the "_|‾ ‾|_" button for channel 1. What happens to the trace? Why?

(Q-23) Now press the "_|‾ ‾|_" button for channel 2 (the trigger level should remain within the peak-to-peak voltage range of channel 1's signal). What happens to the trace? Can you explain this?

You should reset the oscilloscope in preparation for the next section.

F Toys

A *transducer* is a device that can convert energy of some form (e.g., sound or light) into a voltage signal. The oscilloscope can then be used to display the voltage signal, and thus provide information about the original sound or light wave.

For the first part of this section, you will disconnect the function generator from the oscilloscope and replace it with a microphone. Turn the microphone on. Sounds picked up by the microphone will be displayed on the oscilloscope as a voltage signal.

(Q-24) Try to whistle a sustained note into the microphone. If you do this right, you should get a pretty good sine wave on the oscilloscope screen (you may need to play around with the microphone settings to get the most stable voltage signal). Now whistle louder and softer without changing the pitch. What happens to the oscilloscope trace? Which quantity seems to be associated with loudness?

(Q-25) Now whistle higher and lower pitches (try not to change the loudness, although this may prove difficult). What happens to the oscilloscope trace as you change the pitch? Which quantity seems to be associated with pitch? If you were to increase the pitch by an octave, what happens to the oscilloscope trace (be as specific as possible)?

(Q-26) Sing a sustained note into the microphone and note the resulting oscilloscope trace. Is the signal periodic (it will *not* look like a simple sine wave)? Have each lab partner sing the same note into the microphone. Is the oscilloscope trace the same for each person?

(Q-27) A tuning fork can be used to generate a sound with a well-defined pitch (piano tuners used to use tuning forks back in the days before the electric equipment they tend to use now

was invented). Strike the tuning fork and note the resulting oscilloscope trace. It should look like a sine wave. Determine the frequency of the signal (explain how you do this). What happens to the amplitude over time? Why?

For the second part of this section, you should disconnect the microphone (TURN IT OFF PLEASE) and replace it with a photodiode. A photodiode converts electromagnetic energy (i.e., light) into a voltage signal.

(Q-28) You should note a small DC signal (make sure the oscilloscope is set to DC mode). Where do you suppose that signal is coming from? Cover the photodiode with your hand. What happens to the DC signal?

(Q-29) The photodiode can be used to investigate the infrared signals emitted by a TV remote control. Place the infrared emitter of the remote control directly over the photodiode and press one of the buttons and hold it. What sort of signal do you observe on the oscilloscope? In order to answer this question correctly, you must make sure that the *entire signal* fits on the oscilloscope screen. You will need to adjust the VDF and MTB of the oscilloscope. The AUTOSET button is not likely to help you in this case.

(Q-30) Now press different buttons on the remote control and make note of the oscilloscope trace in each case. Can you explain how the remote control sends information, such as channel selection and volume control, to the television set (i.e., how does the TV know what button you are pushing on the remote control)?